THE EFFECT OF FIBRE CUTS ON THE TENSILE BEHAVIOUR OF HYBRID CARBON FIBRE/SELF-REINFORCED POLYPROPYLENE COMPOSITES

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ABSTRACT

Fibre cuts were introduced into carbon fibre/self-reinforced polypropylene (SRPP) to achieve more control over the energy release upon fracture of the carbon fibre ply. The goal was to provide a gradual transition from the carbon fibre failure to the SRPP failure. The cuts were applied either manually or by a laser. Increasing the number of cuts for a given total cut length reduced the ultimate failure strain of the hybrid composite without a more gradual failure behaviour. Increasing the cut length increased the ultimate failure strain and yielded a more gradual transition. Nevertheless, it was found to be difficult to achieve fragmentation, or multiple fracturing of the carbon fibre plies. The extent of delaminations was strongly affected by the presence of the cuts.

1 INTRODUCTION

High stiffness and high failure strain are often mutually exclusive properties in fibre-reinforced composites. Carbon fibre composites have a high stiffness, but a low failure strain. Self-reinforced composites do have a high failure strain, but lack stiffness. A particular successful example is self-reinforced polypropylene (SRPP) [1-4]. These composites consist of highly oriented PP tapes in an unoriented matrix of the same polymer type.

Recently, we have proposed hybridisation as a way to combine the high failure strain of self-reinforced composites with the high stiffness of carbon fibre composites [5, 6]. The main challenge of carbon fibre (CF)/SRPP hybrids is to find appropriate ways of dealing with the significant load drop when the carbon fibre plies fail. This releases a large amount of energy, which can go either into the creation of a delamination or into damage to the SRPP. Any damage to the SRPP will result in a strong reduction of the ultimate failure strain of the hybrid composite. Reducing the amount of released energy is therefore crucial in optimising the performance of hybrid SRPP.

Pre-cutting the carbon fibre-reinforced PP (CFRPP) at certain locations should provide additional control over the released energy. Researchers have used discontinuous plies for various reasons, such as improving the formability [7], mitigating stress concentrations at free edges [8], achieving pseudo-ductility [9] and improving toughness [10]. In all of these works plies were cut over the entire width, whereas in this study they were cut only partially. By doing so, fibre continuity is ensured for at least part of the ply, which should limit the strength reduction. The main aim of using these cuts is to decouple the stiffness of the CF plies from their strength. This should allow us to increase the stiffness, while avoiding the large stress drop that often leads to a reduced ultimate failure strain [6]. There are however many different possible cut patterns. Here, the focus is on understanding the influence of the number of cuts and the cut length.

2 MATERIALS AND METHODS

2.1 Materials

Woven PP tapes were provided by Propex Fabrics GmbH (Germany). This twill 2/2 weave was overfed, which means that the width of the tapes was larger than the spacing between neighbouring tapes. Therefore, some of the tapes were folded [11]. The areal density of the weave was 130 g/m^2.

Unidirectional carbon fibre preforms were provided by Chomarat (France). The preform had an areal density of 73 g/m² and a width of 25.4 cm. It contained dry T700SC-50C carbon fibres and no binder.

Propex Fabric GmbH also provided 20 µm thick PP film. This film was used for two purposes: to impregnate the carbon fibre preform and to increase the matrix fraction, thereby improving the bonding between the CF ply and SRPP. The film is made from the same PP grade as the tapes, and has a melting temperature of 163°C.

2.2 Prepreg production

The carbon fibre preform was cut to a size of 150 x 300mm and impregnated using the 20 µm PP films. A film was placed above as well as below the carbon fibre preform, which should lead to an estimated fibre volume fraction of 51% in the CF ply. This layup was placed into a hot press and impregnated, after which the press was cooled down in about 5 min. The processing time, temperature and pressure were optimised to maximise impregnation quality and minimise fibre misalignment. The optimal conditions were to press at 10 bar and 188°C for 5 min.

The carbon fibre prepregs were then partially cut to introduce discontinuity into the brittle phase of the hybrid composite. It should be emphasised that only the prepregs were cut, as this was performed prior to hybridisation. The cuts were made either manually using a sharp knife or automatically by a laser, and the results of both approaches will be compared. All cuts were made at a 90° angle with respect to the carbon fibre direction (see Figure 1). Cuts were made at three locations along the sample length, and the spacing between these lines was always 40 mm. The cut height (opening) was always 100 µm and is related to the width of the laser beam. All parameters of the cut pattern are summarised in Table 1.

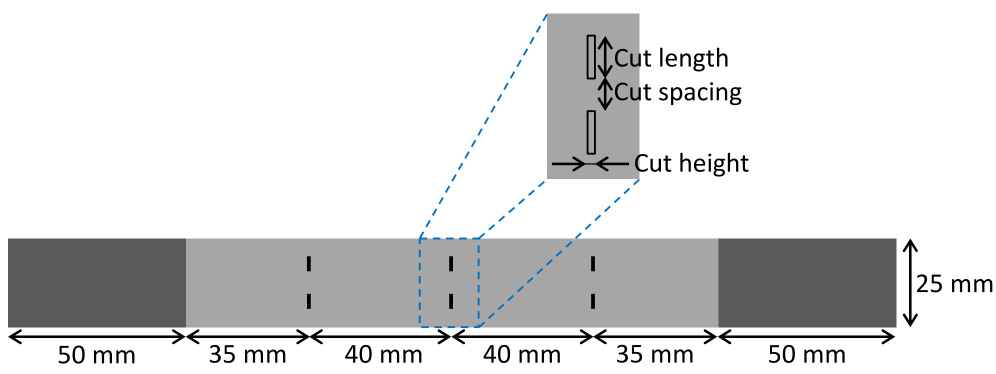

Figure 1: Schematic illustration of a cut pattern with 2 cuts over the width. This is illustrated on a tensile sample to highlight the relative positions of the cuts, even though the cuts were applied prior to hybridisation and cutting of the tensile samples.

Layup #	0	1	2	3	4	5
Cutting method	None	Manual	Laser	Laser	Laser	Laser
Number of cuts over width	/	1	1	10	1	1
Cut length (mm)	/	10	10	1	6	15
Cut spacing (mm)	/	/	/	1.5	/	/

Table 1: Overview of the different cut patterns.

2.3 Hot compaction

The hybrid layups were always the same, apart from the type of fibre cuts in the prepreg. This layup was (S/S/S/F/C/F/S/S/S), where S, F and C stand for SRPP, film and carbon fibre prepreg, respectively. This layup was inserted into a preheated hot press at 188°C for 5 min, after which the press was cooled down to 40°C in 5 min. A pressure of 40 bar was exerted on the material during the entire process.

2.4 Tensile tests

Tensile tests were performed on an Instron 4505 tensile machine with a load cell of 100 kN. A strain rate of 5%/min was applied. All specimens were 25 mm wide and 250 mm long (see Figure 1), and were tested at a gauge length of 150 mm. End tabs were not used, but were replaced by sanding paper to ensure sufficient friction. The front and back surface of the specimen was tracked using a camera. A strong light was aimed at the front surface to enable the camera in the back to reveal failure of the carbon fibre layer. Half of the width of the front surface was covered with a speckle pattern for digital image correlation to measure strains.

Several parameters were derived from the stress-strain diagrams. The tensile modulus was calculated as the slope in the strain interval from 0.1% to 0.3%. The stress at the CFRPP peak and the stress immediately after this peak were used to calculate the height of the stress drop. The ultimate failure strain was calculated as the point where the stress dropped below 20% of the strength. From the front and back images, two additional parameters were measured. Firstly, the number of fractures of the CFRPP layers was counted. Ideally, the cuts should trigger these fractures, leading to a total of 3 CF ply fractures. Secondly, the initial delamination length was measured from the images. This was identified based on the colour change occurring due to the occurrence of a delamination.

3 RESULTS

The results are split up into three different investigations: the cutting method, the number of cuts and the cut length. Layup 2 will be used in all of these investigations, as it serves as the basic cut pattern.

3.1 Influence of cutting method

The basic idea of pre-cutting the prepregs is to reduce the amount of energy released upon fracture of the pre-cut ply. This should help to reduce the initial delamination length, and thereby the height of the stress drop at fracture. The first step in the research is finding a suitable method for applying these pre-cuts. This section therefore compares hybrids with manual and laser cuts to hybrids without any cuts. This section therefore compares layups 0, 1 and 2 from Table 1, which are labelled as “no cuts”, “manual cuts” and “laser cuts”, respectively.

The initial cuts were slender, and had a thickness of about 100 µm. After hot compaction, the shrinkage of the SRPP causes these cuts to open up more (see Figure 2). This is true irrespective of the way the cuts were applied. The main advantage of laser cutting therefore lies in a better control and the possibility for creating more complex patterns.

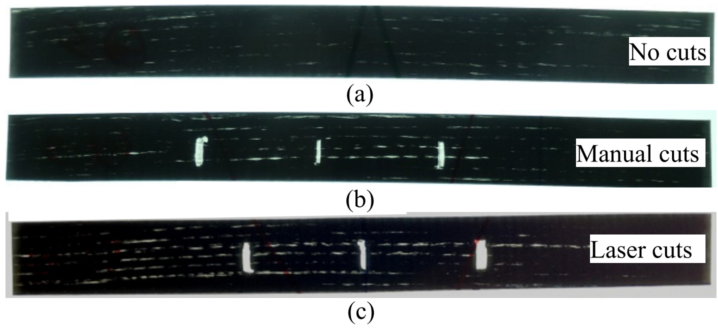

Figure 2: Photographs of the cuts in the hybrid samples, revealing that the cuts have opened up during production: (a) layup 0 without cuts, (b) layup 1 with manual cuts, and (c) layup 2 with laser cuts.

The presence of cuts had a significant influence on the tensile behaviour (see Figure 3). It reduced the height of the CFRPP peak and caused the CFRPP to fail at a slightly lower failure strain. Changes in the tensile modulus were insignificant (see Table 2). The effect that was aimed for however, was only partially achieved. The presence of cuts did significantly reduce the initial delamination length and the height of the stress drop, but this did not prevent damage to be inflicted to the SRPP layers. This can be observed from the reduction in the ultimate failure strain (see Table 2), but also from the overall trend in the tensile diagrams (see Figure 3).

One specimen with manually cut prepregs showed fragmentation, as it fractured at two of the cuts. Unfortunately, this was the only specimen showing this behaviour.

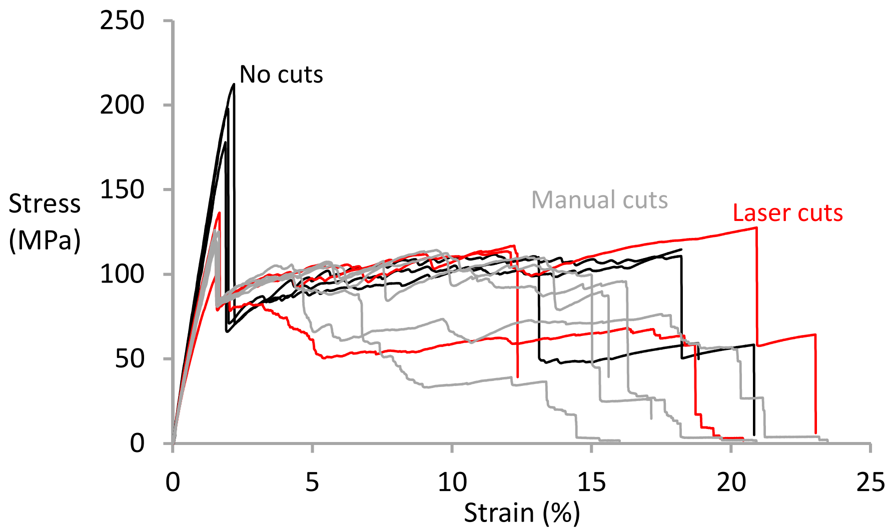

Figure 3: Stress-strain diagrams of hybrids showing that introducing cuts reduces the CFRPP peak, and increases the scatter in the SRPP peak. The cutting method has no clear influence on the tensile response.

	Cutting method		
	None	Manual	Laser
Layup #	0	1	2
Modulus (GPa)	10.8 ± 0.6	9.5 ± 0.5	10.6 ± 0.3
Stress at CFRPP peak (MPa)	196 ± 14	121 ± 4	129 ± 11
Stress after drop (MPa)	69.5 ± 2.3	82.5 ± 1.4	81.7 ± 0.3
Stress drop (MPa)	126.5 ± 12.1	38.7 ± 5.2	47.1 ± 10.8
Strain at CFRPP peak (%)	2.02 ± 0.13	1.57 ± 0.05	1.61 ± 0.09
Ultimate failure strain (%)	18.14 ± 4.06	16.2 ± 2.5	16.6 ± 6.1
Initial delamination length (mm)	30.7 ± 1.3	12.2 ± 0.6	14.2 ± 2.7

Table 2: Tensile parameters of the hybrids revealing the effect of the introduced cuts.

3.2 Influence of the number of cuts

A cut can be applied as one long cut, or can be divided in multiple, short ones. For this purpose, layups 2 and 3 (see Table 1) are compared in Figure 4 and Table 3. The main influence of the shorter cuts is the drastic reduction in the ultimate failure strain. The multiple cuts also reduced the height of the stress drop, the strain at the CFRPP peak and the initial delamination length, which may indicate that the total length was slighly larger than 10 mm.

One specimen with 10 cuts of 1mm revealed fragmentation, similar to the observation for one specimen with manual cuts in the previous section. Fragmentation was not observed in any of the other specimens.

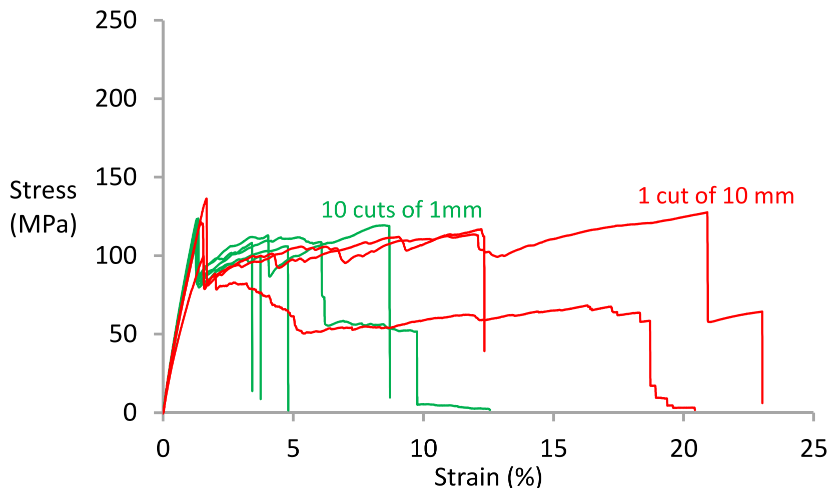

Figure 4: Stress-strain diagrams of hybrids showing that more but shorter cuts reduce the ultimate failure strain significantly.

	1 cut of 10 mm	10 cuts of 1 mm
Layup #	2	3
Modulus (GPa)	10.6 ± 0.3	10.7 ± 0.4
Stress at CFRPP peak (MPa)	129 ± 11	118.4 ± 5.9
Stress after drop (MPa)	81.7 ± 0.3	84.2 ± 3.1
Stress drop (MPa)	47.1 ± 10.8	34.2 ± 3.3
Strain at CFRPP peak (%)	1.61 ± 0.09	1.32 ± 0.04
Ultimate failure strain (%)	16.6 ± 6.1	6.10 ± 2.94
Initial delamination length (mm)	14.2 ± 2.7	8.9 ± 0.5

Table 3: Tensile parameters showing that 10 cuts of 1 mm are more detrimental to the ultimate failure strain than 1 cut of 10 mm.

3.3 Influence of cut length

Whereas the previous section changed the number of cuts without changing the overall cut length, this section will change the cut length. By increasing the cut length, the amount of released energy upon CFRPP fracture can be reduced, which should help in reducing the initial delamination length and the damage to the SRPP.

Increasing the length of the cut indeed reduced the height of the CFRPP peak (see Figure 5). This also slightly increased the stress level immediately after the CFRPP peak (see Table 4). Combining these two aspects together lead to a strong reduction in the height of the stress drop, which again reduced the initial delamination length. Unfortunately, this still resulted in a large scatter on the ultimate failure strain. None of the specimens were fragmented.

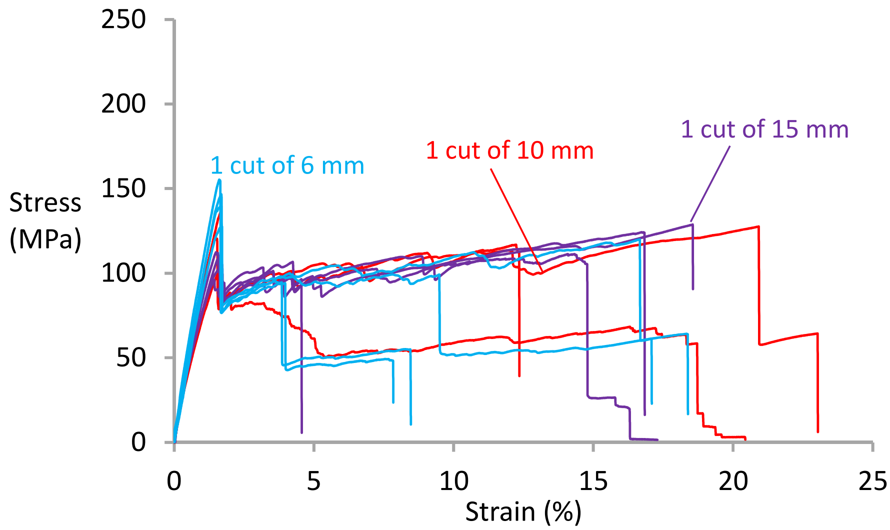

Figure 5: Stress-strain diagrams of hybrids showing that increasing the length of the cut reduces the CFRPP peak and increases the ultimate failure strain.

	Length of the cut		
	6 mm	10 mm	15 mm
Layup #	4	2	5
Modulus (GPa)	10.2 $\pm$ 1.9	10.6 $\pm$ 0.3	9.9 $\pm$ 0.4
Stress at CFRPP peak (MPa)	142 $\pm$ 11	129 $\pm$ 11	105.1 $\pm$ 4.5
Stress after drop (MPa)	78.2 $\pm$ 2.0	81.7 $\pm$ 0.3	83.6 $\pm$ 1.5
Stress drop (MPa)	63.7 $\pm$ 11.6	47.1 $\pm$ 10.8	21.5 $\pm$ 6.0
Strain at CFRPP peak (%)	1.69 $\pm$ 0.03	1.61 $\pm$ 0.09	1.64 $\pm$ 0.08
Ultimate failure strain (%)	12.95 $\pm$ 5.56	16.6 $\pm$ 6.1	13.69 $\pm$ 6.28
Initial delamination length (mm)	15.6 $\pm$ 1.7	14.2 $\pm$ 2.7	9.9 $\pm$ 1.4

Table 4: Tensile parameters showing that increasing the cut length reduces the CFRPP peak, but increases the ultimate failure strain.

4 CONCLUSIONS

Partially cutting the carbon fibre prepregs of hybrid SRPP was shown to provide additional control over the tensile properties. The cuts can reduce the strength of the CFRPP prepregs without affecting the stiffness. This proved helpful in reducing the height of the stress drop upon CFRPP failure, which also reduced the initial delamination length. Unfortunately, this did not result in a larger ultimate failure strain, nor did it reduce the large scatter in the ultimate failure strain. Resolving this issue will require limiting the damage inflicted to the SRPP upon CFRPP failure. This could potentially be achieved by larger cuts or by inserting an additional layer in between the SRPP and CFRPP.

The cuts were also insufficient to cause multiple fractures of the CF plies. While this did happen in a few samples, it never happened in all three possible locations. Larger cuts seem to be necessary to trigger fragmentation in these hybrids.

Further work will include more complex cut patterns such as angled cuts, which could result in a more gradual failure of the prepreg.

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